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ABSTRACT

This paper describes the highly successful 24 hour trilateration tracking and orbit determination test conducted on 3 November 1974. In this test a new method of accurately computing geostationary spacecraft orbits was applied to the Applications Technology Satellite (ATS-6). Conventional satellite tracking involves a network of radio tracking stations each serving as a separate interrogation and data collection terminal. However with this new technique a single tracking station interrogates several strategically deployed ground-based transponders via the synchronous satellite whose orbit is to be determined. The ATS-6 tracking data measurement noise over the 24 hour period was observed to be 0.3 mm/sec in range rate and 1.5 meters in range. By means of overlap orbit computation using 2 separate tracking data bases the ATS-6 total position and velocity uncertainties were determined to reach a minimum of 30 meters and 0.2 cm/sec respectively. The maximum position and velocity uncertainty over this same time

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period was determined to be approximately 250 meters and 2 cm/sec respectively. A position determination using simultaneous tracking of the NASA-GSFC site by ATS-6 and ATS-3 was also performed. Station location recovery was to an accuracy on the order of 100 meters over the first 10 hours of tracking.

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RESULTS OF THE 3 NOVEMBER 1974 APPLICATIONS TECHNOLOGY SATELLITE-6 (ATS-6) TRILATERATION TEST

1.0 INTRODUCTION

Knowledge of a satellite's position in space is an essential aspect of day-to-day satellite utilization. The Measurements Evaluation Branch, NASA-GSFC, has developed a new method for accurately predicting the position of geostationary satellites such as currently used for worldwide weather observation, television relay, and transoceanic communications.

Conventional satellite tracking and subsequent position determination involves a network of manned radio or laser tracking stations each serving as a separate data collection terminal. However with this new technique a single tracking station sends signals to several strategically deployed unmanned low cost transponders via the satellite whose position is to be determined. The time required for the radio signals to make the round trip to-and-from each transponder is measured at the transmitter site.

This time delay is measured by comparing zero crossings of a reference tone at the transmitting site to zero crossings of the tone which experienced the round trip time delay while modulated on a carrier. Low frequency tones are used to resolve ranging ambiguities. The tones transmitted in the system used to track ATS-6 are 8 Hz, 32 Hz, 160 Hz, 800 Hz, 4 kHz, 20 kHz, and 100 kHz.

The 100 kHz high resolution tone is that used to make the final time delay determination which is recorded in the data message. Also time delay rate measurements are made by coherently observing the carrier shifted Doppler. The basic tracking system used to track ATS-6 is the type of narrowband phase modulated scheme NASA has used for years to track satellites in range and range-rate (Ref. 1). All such systems measure total radio wave propagation path changes in terms of carrier frequency and tone frequency phase shifts. The electronic subsystems associated with ATS-6 satellite tracking are described in great detail in References 2 through 10.

The time delay and delay rate measurements derived from transponder tracking via such geostationary satellites as ATS-6 are different from conventional tracking in that 4 distinct propagation paths are involved. In the orbit determination program (NASA-GSFC Navigation Analysis Program) the four radio propagation paths are considered separately and the final orbit solution arrived at iteratively. This analysis program is a generalized least squares parameter estimation program designed to accept and process numerous types of tracking observations, and includes algorithms for rigorous treatment of single or multi-satellite time delay and delay rate measurements (Ref. 11). The geopotential model can be selected from any of a number of available gravity field models. One such field currently used in this program is the Goddard Earth Model (GEM-2) which is given in terms of spherical harmonics to order, degree 22. Lunar and solar perturbations are provided by means of the JPL ephemeris residing on permanent disk file at the NASA-GSFC IBM 360/95 computer facility. The Navigation Analysis Program as just described has been used to calculate accurate predictions of geostationary satellite position up to several weeks in advance. This new satellite position determination technique has been successfully demonstrated during numerous NASA tests beginning with the launch of ATS-6 (May 30, 1974) through the present time (April 1975). Successful trilateration orbit tests have been conducted with ATS-6, ATS-3 and the Synchronous Meteorological Satellite (SMS-1).

2.0 TRACKING DATA EVALUATION

The special purpose tracking system used in this experiment has been extensively evaluated over the past 3 years during all phases of design, development and implementation. The most recent tests have involved the tracking of strategically deployed transponders via ATS-6. Such tests were conducted to determine the orbit computation accuracy which can be expected during satellite-to-satellite tracking experiments. Several 24 hour tracking tests have been performed. Results have been of consistently high quality with data noise typically from 0.2 to 0.5 mm/sec for range rate and from 1 to 2.5 meters in range. This noise level is in agreement with that predicated theoretically (Refs. 3, 12 and 13).

The basic configuration for trilateration tests is shown in Figure 1. A transmitter is located at one site and transponders are sequentially interrogated at remote sites. The nominal uplink frequency is 6 GHz to ATS-6, 2.1 GHz ATS-6

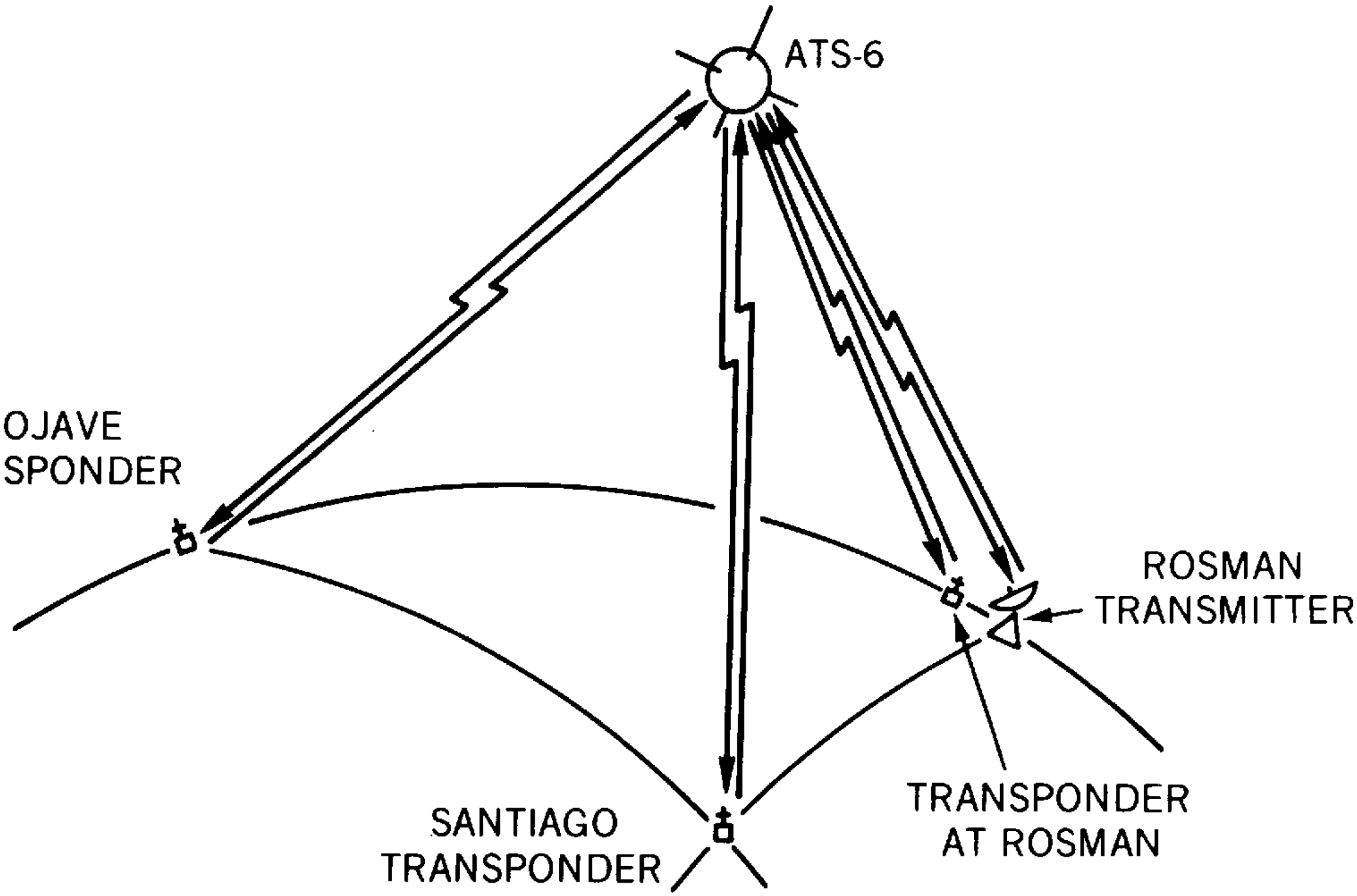

Figure 1. ATS-6 Trilateration Tracking

to transponder, 2.2 GHz transponder to ATS-6, and 4 GHz ATS-6 to interrogating station. During the test described in this report a transponder was also located at the NASA Test and Training Facility (NTTF-GSFC). Also a transmitting station was located at the Mojave site which also interrogated all transponders sequentially. The latter transportable station was being evaluated in preparation for operation during the Apollo-Soyuz mission and has since been installed at Madrid, Spain.

The availability of essentially 2 separate data sets (Mojave and Rosman) covering the same 24 hour period makes the 3 November 1974 test extremely valuable in assessing orbit computation accuracy. The tracking schedule implemented is shown in Figure 2. The two interrogating sites are identified in Figure 2 under TRANSMITTER as Rosman, North Carolina and the Mojave, California "Hybrid Transportable" station. The transponders were located at Rosman, Mojave, NTTF Greenbelt, Maryland and Santiago, Chile. Each data stretch was approximately 5 minutes long and the data rate was one sample per 10 seconds. As an example, at 14 hours UT (Fig. 2) the Mojave Hybrid terminal interrogated the Mojave located transponder for five minutes. At 15 hours UT the Mojave Hybrid interrogated the NTTF located transponder and so on. In this manner a total of 48 data arcs of range and range rate were recorded. The RMS data noise for each 5 minute data span was determined by means of 5th degree polynomial smoothing. This smoothing is an analysis option of the Navigation Analysis Program tracking data preprocessor. The majority of the data

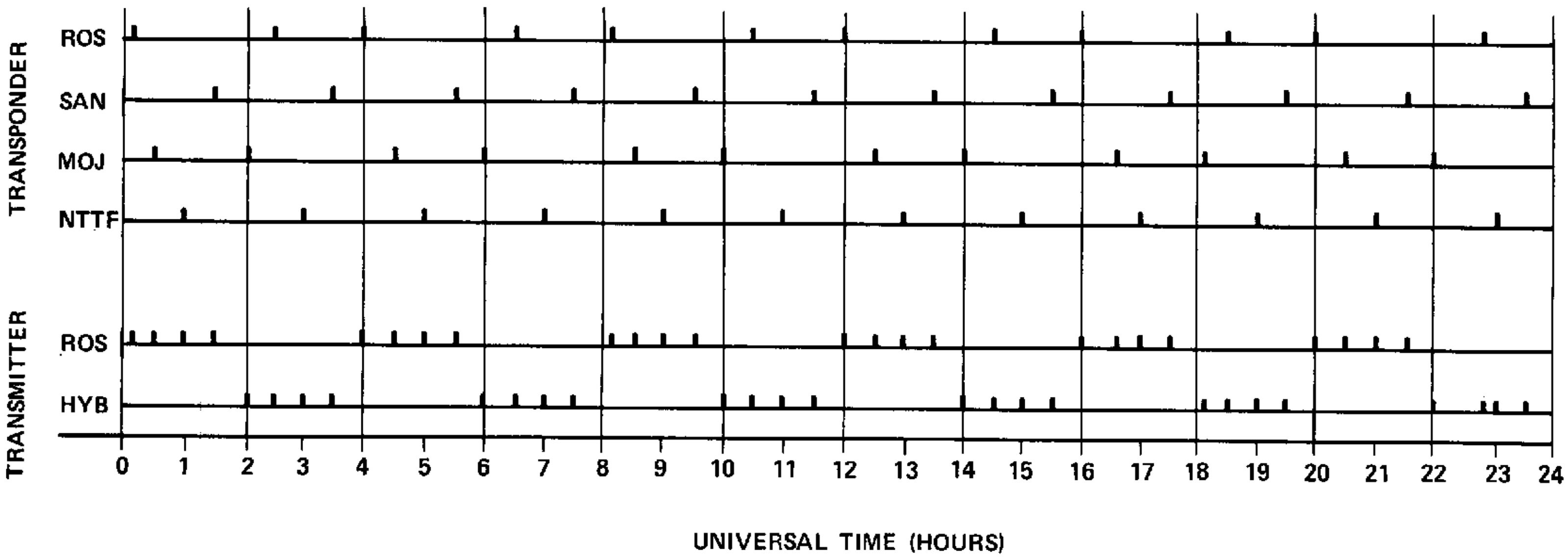

Figure 2. Tracking Schedule 3 November 1974

arcs were seen to be valid (Ref. 14) and the noise results are as shown in Figure 3.

The range rate noise is directly related to the coherent Doppler averaging time and most tests to date have used a 10 second data sample interval with 5 seconds Doppler averaging. The range noise is due primarily to tracking system quantization of the 100 kHz range tone time delay measurement.

It should be mentioned that the range and range rate between any fixed Earth site and a geostationary satellite are not constant but rather vary considerably over a 24 hour period. Figure 4 indicates the slant range variation observed from Rosman to ATS-6. Basically this is the total range measured, Rosman transmitter to Rosman transponder via ATS-6 divided by 4. "Total range" is defined as the measured time delay multiplied by the speed of light, 2.997925×10^8 meters/sec. With reference to Figure 2, this tracking combination occurred 6 times spaced over the 24 hour period. The peak range rate excursion can be estimated from Figure 4 by multiplying one half of the peak range variation by 2π divided by the period in seconds. The period is 86400 seconds and the maximum range rate is seen to be 8.5 meters per second. That is, over the 24 hour period the range rate contribution from Rosman to ATS-6 will vary from 8.5 meters/sec to zero meters/sec in a sinusoidal manner. In fact, the range variation over a 24 hour period can be estimated for any path between a fixed point on Earth and the geostationary spacecraft as follows:

$$\Delta R \doteq 1.2a \sin \theta \sin i \tag{1}$$

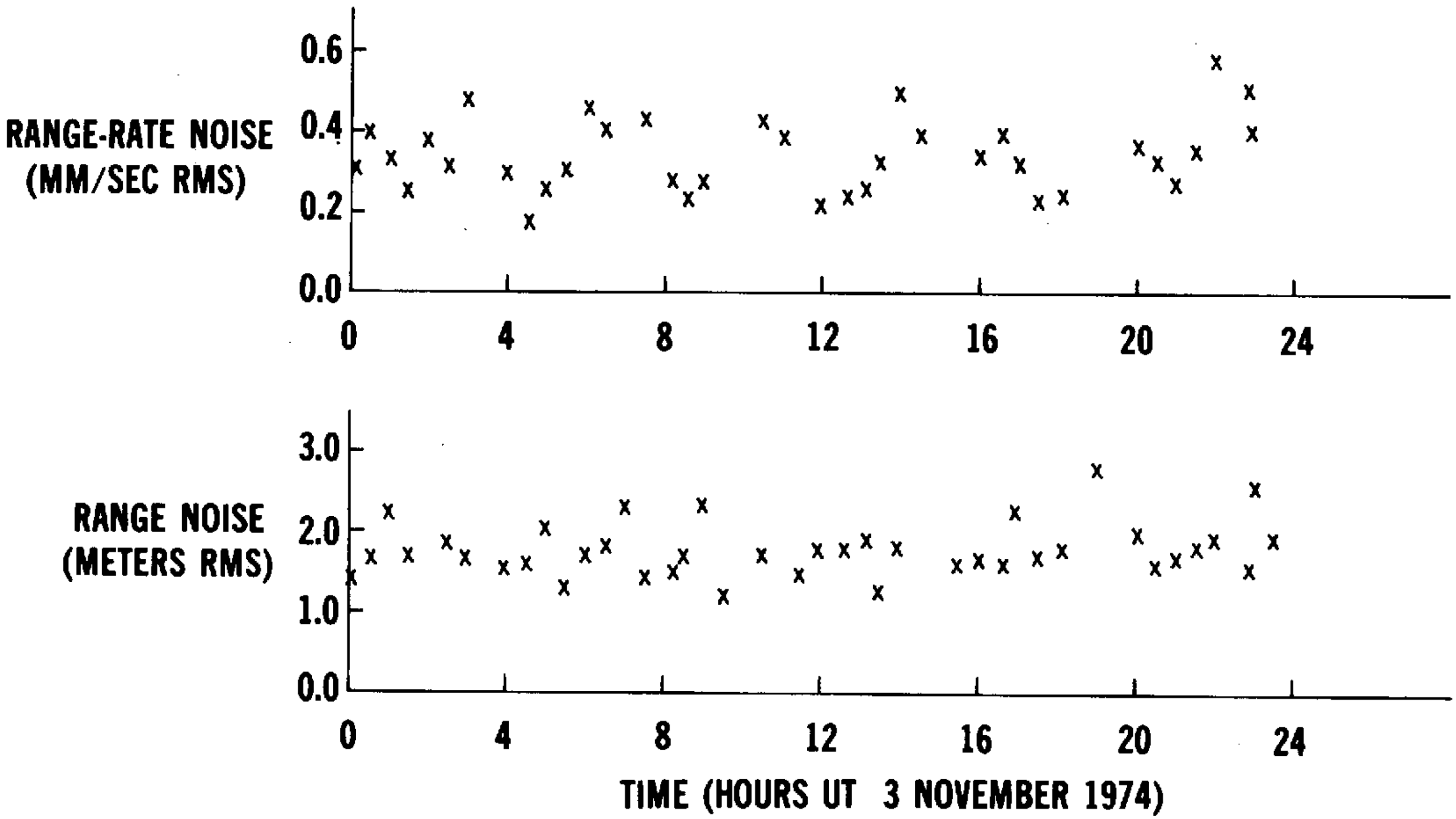

Figure 3. Tracking System Noise

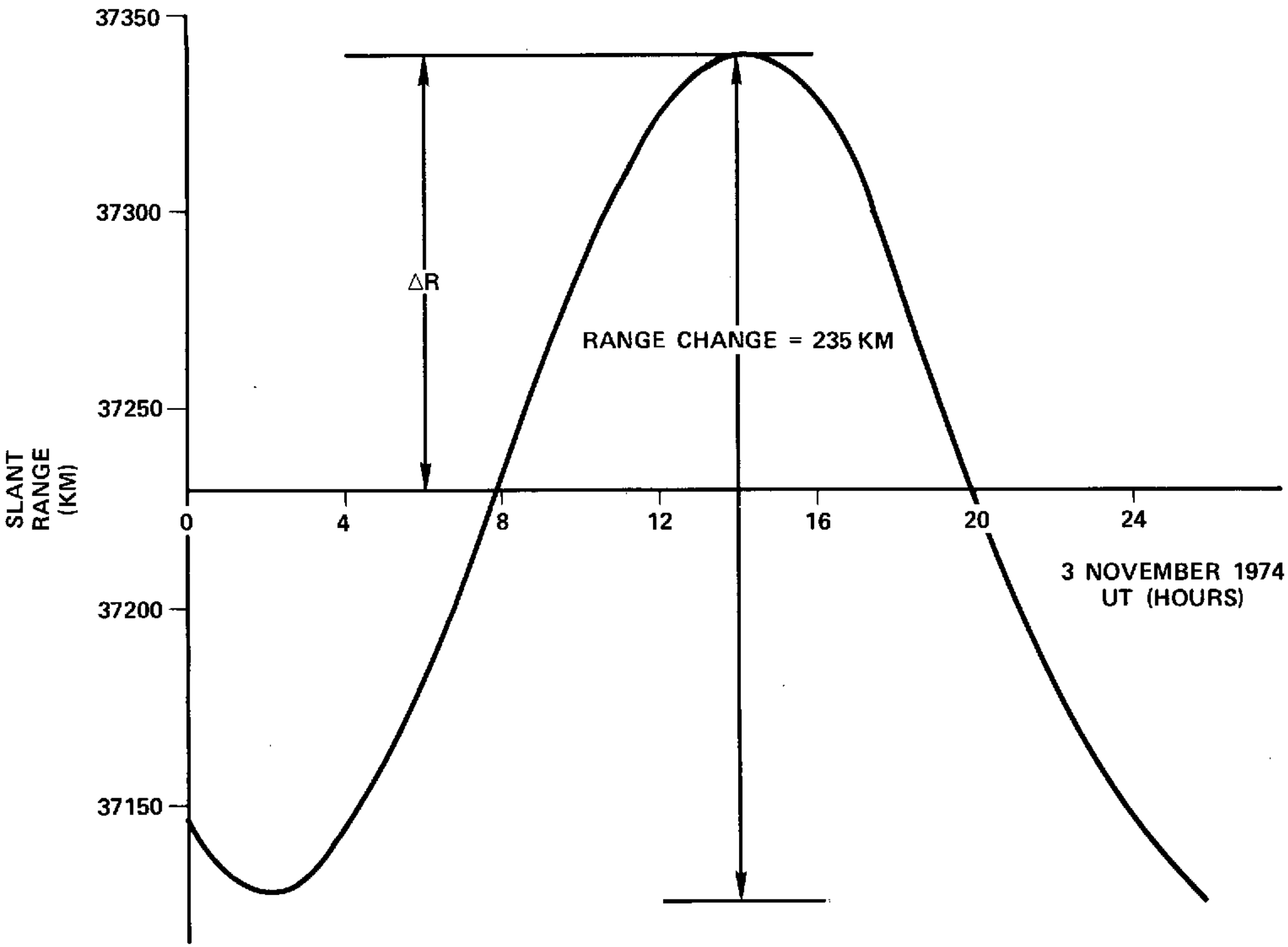

Figure 4. Rosman to ATS-6 Slant Range

where

ΔR = 1/2 of total range variation

a = Earth radius $\doteq$ 6378 km

θ = station latitude (for Rosman $\doteq$ 35.2°)

i = geostationary satellite inclination (for ATS-6 $i \doteq$ 1.6°)

Using Equation 1 for Rosman the approximate total range excursion ($2\Delta R$) is calculated as 246 km as compared to 235 km observed from the raw data. Equation 1 can be used to obtain observability estimates to within 5%. The above was derived for a geostationary satellite at approximately the same longitude as the Earth site. However it can be shown that this result is not a critical function of station longitude and if the site can view the geostationary satellite the range variation will in any case be correct to about 10%. The combined path measurement will of course be a function of each path contribution and further analysis must incorporate more rigorous procedures. It might be inferred (from Eq. 1) that the range rate between a site on the equator (θ = 0°) and an inclined geostationary satellite is zero. The latter value however is not zero but a small double frequency range rate variation. It can be shown that the range rate between an Earth site and a geostationary satellite is approximated by:

$$\dot{R} \doteq 1.2a\,\omega \sin i \left(\sin\theta \cos\omega t - \frac{\cos\theta \sin i \sin 2\omega t}{2}\right) \tag{2}$$

In Equation 2 all terms are as previously defined and ω is the angular frequency corresponding to the 24 hour period. $\dot{R}$ is the range rate between Earth site and synchronous satellite.

The foregoing discussion simply points out that so called "geostationary satellites" actually undergo a significant amount of periodic motion relative to a fixed Earth site. It is this motion relative to many sites which can be observed to perform an accurate geostationary orbit computation. The inclination, i, will gradually change with time and occasional onboard station keeping is necessary if a fixed inclination is desired. Nominal values of inclination maintained for current NASA geostationary spacecraft extend from 1.5° to 6°. Such synchronous orbits are apparently more stable than zero degree inclination orbits.

3.0 ORBIT COMPUTATION ANALYSIS

One method of assessing orbit computation accuracy is to observe orbit computation residuals, that is the difference between observed and calculated tracking observations. The data base indicated in Figure 2 was corrected for all known calibration biases. This included all transponder delays, station delays and inserted Doppler bias offsets. The overall data handling is as indicated in Figure 5. All of the 3 November 1974 trilateration range data was used to obtain an ATS-6 orbit. Figure 6 is the mean residual plot over the 24 hour period. Each point on the graph is the mean value of the difference between observed and calculated equivalent one way range (i.e., from transmitter to transponder in any given combination). Each point represents approximately 5 minutes of tracking time and includes computed adjustments to nominal calibration delays. Comparable results have been obtained with "Doppler only" solutions and "Doppler plus range data solutions." Typical orbit residuals

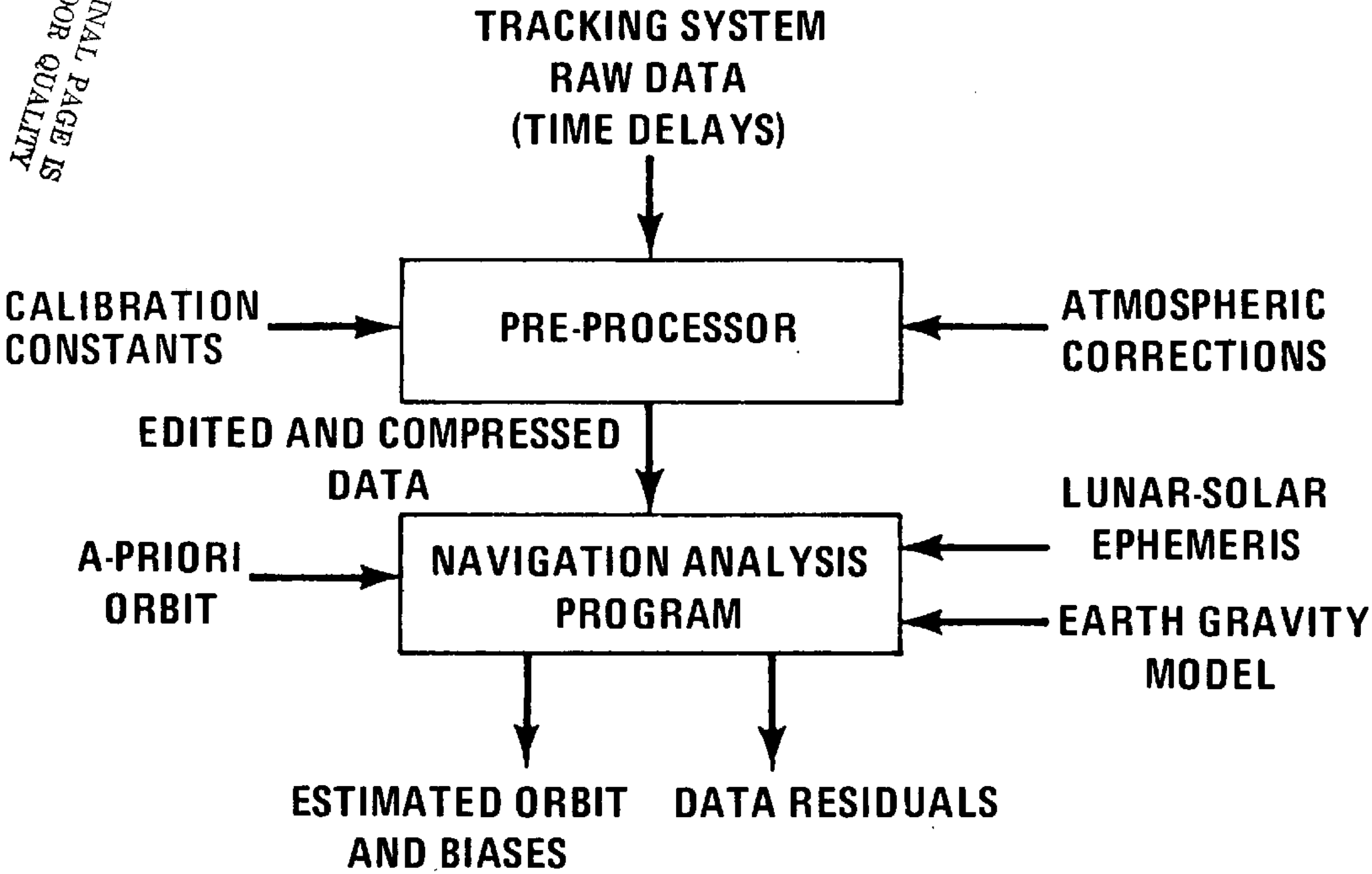

Figure 5. Data Processing

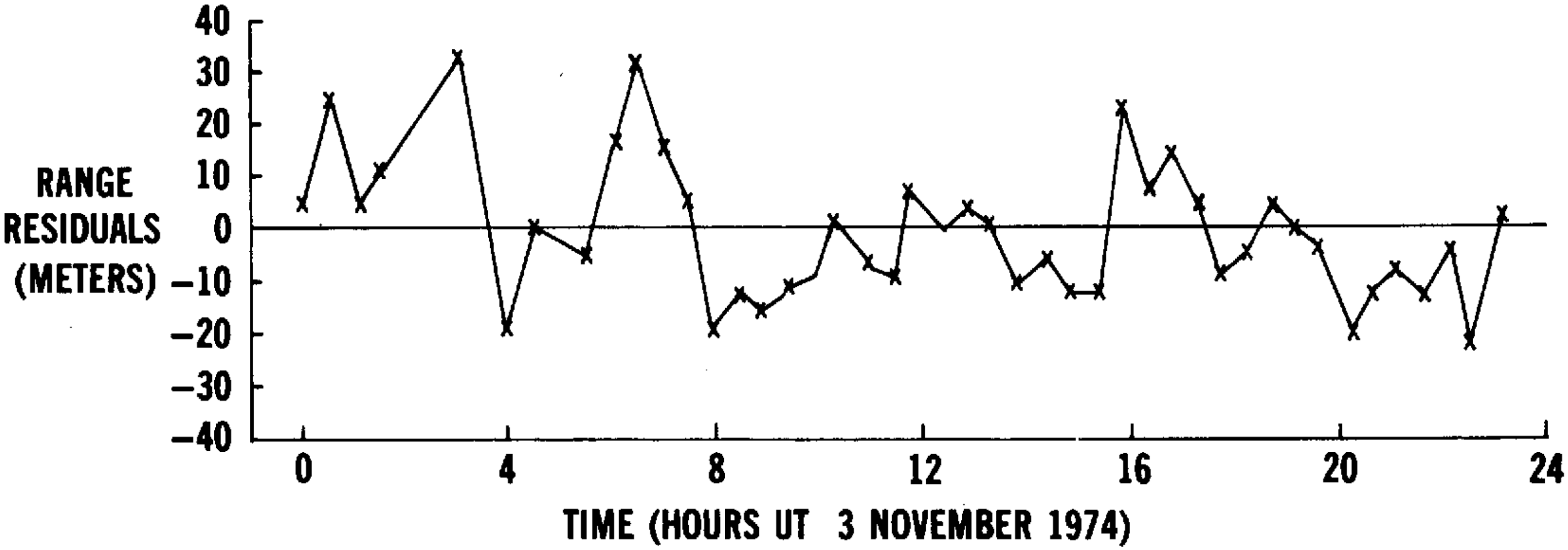

Figure 6. ATS-6 Orbit Residuals

in range are seen to be on the order of 20 meters. The RMS noise levels about the mean value have been observed to be at the levels indicated by Figure 3.

The ATS-6 vector recovered using all ranging data in the Navigation Analysis Program as given by:

$$x = 25907485 \text{ meters}$$

$$y = -33239484$$

$$z = 677879$$

$$\dot{x} = 2426.192 \text{ meters/sec}$$

$$\dot{y} = 1889.945$$

$$\dot{z} = 48.268$$

where the epoch is 0000 hours UT 3 November 1974.

The orbit computation modeling includes solar pressure, Earth gravity, and sun-moon gravity effects. Lunar gravity effects alone have been shown to introduce several kilometers of peak-to-peak variations in ranging measurements to synchronous spacecraft (Ref. 15).

Another means of assessing orbit computation accuracy is to overlap independently derived orbits and comparing the position and velocity differences. Again the 3 November 1974 test data base was ideal for such a comparison. Over the 24 hours half of the data was taken at the Rosman tracking site and half at the Mojave site. In each case transponders at Rosman, Mojave, Santiago and Goddard were tracked via ATS-6. Each data subset spanned 24 hours thus assuring observation of one complete orbit. The results are indicated in Figures 7 and 8. The position accuracy so determined is seen to approach 20 meters at the mid-data span. The corresponding velocity determination error is 0.2 cm/sec. The maximum overlap error is seen to be 250 meters and 1.7 cm/sec respectively and occurs at the time corresponding to the beginning of the data span (i.e., 0 hours UT).

The fact that the minimum overlap error occurs at 12 hours UT appears consistent with the fact that knowledge of the ATS-6 motion is derived in this case from equal spans of data prior to an after this point in time.

Further analysis has shown that due to uncertainties in gravity field modeling, station location error, solar pressure modeling and so on the ATS-6 position error in this case periodically increases after a week of vector prediction to approximately 2 km in the X component, 2 km in the Y component and 300 meters in the Z component. This is the propagated error relative to an Earth centered fixed coordinate system. Similarily, the corresponding propagated velocity components are 15 cm/sec for $\dot{x}$, 15 cm/sec for $\dot{y}$ and 0.2 cm/sec for $\dot{z}$. The periodic nature and interpretation of such orbit error propagation is a subject of ongoing study (see for example, Ref. 16).

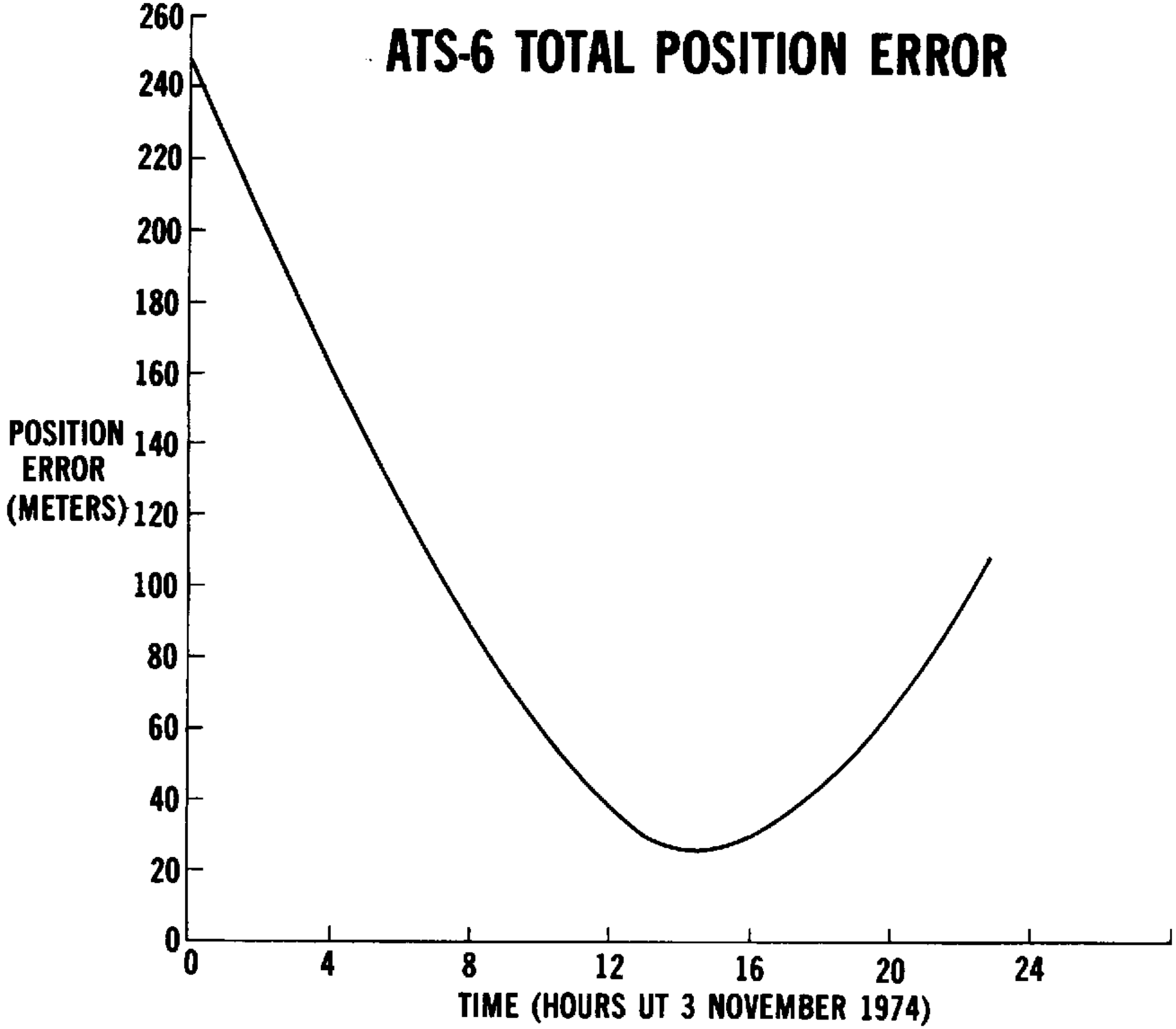

Figure 7. ATS-6 Total Position Error

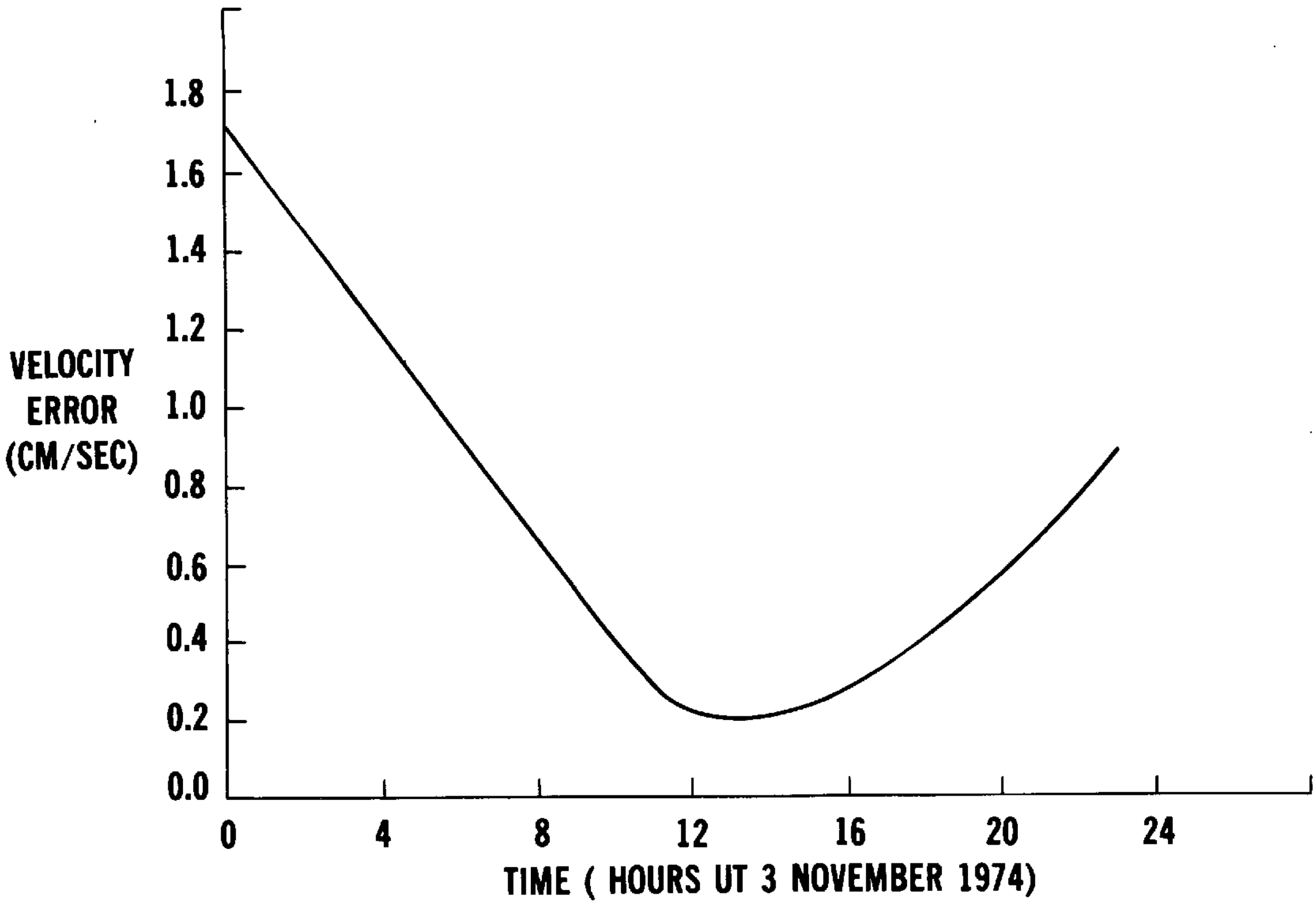

Figure 8. ATS-6 Total Velocity Error

4.0 STATION LOCATION DETERMINATION

Geostationary satellites have great potential for use in such applications as maritime navigation where global coverage is essential. The ATS-6 PLACE experiment for example, is designed to demonstrate such a capability using geometric trilateration (Ref. 17). The advantage of using geometric solutions is that the computer programming required is relatively simple. One scheme is to interrogate the unknown site simultaneously from two spacecraft such as ATS-3 and ATS-5 using a single transmitter site, for example Rosman. A disadvantage to this approach is that the interrogation times, and hence potential accuracy, is limited by the orbital motions. That is, in a geometric solution data must be taken continuously to determine both satellite position and position of the point being "navigated" on the Earth's surface. If however, the satellite orbits are accurately known it should be possible to determine an unknown site in latitude and longitude in a matter of seconds. Unfortunately, routine orbit computation predictions in the past have in general not been sufficiently accurate to permit quick and accurate Earth position fixes.

This foregoing leads to the reason for the second phase of the 3 November 1974 experiment where ATS-3 was independently tracked over the same 24 hour period by the G. E. VHF ranging station at Schenectady, N. Y. via transponders at NTTF-GSFC, Westford, Mass., Daytona Beach, Fla., Kings Point, N.Y. and Shannon, Ireland. Using this data an orbit determination was made for ATS-3.

Since the particular Goddard site used at NTTF is known to within 10 meters, the mutual ranging from ATS-3 and ATS-6 permitted:

1. A further assessment of overall orbit computation accuracy
2. A means for investigating the application of well determined orbits to rapid navigation fixes.

This navigation analysis is still continuing, however the results to date have been very encouraging. The G. E. VHF tone burst ranging system description as applied to ATS-3 orbit computation is presented in detail in Reference 15 and will not be repeated in this report. This system operates at a 149.2 MHz up-link frequency from Schenectady. This is translated to 135.6 MHz at ATS-3 for transmission to the remote transponder. After interrogation the transponder retransmits at 149.2 MHz which in turn is translated to 135.6 MHz and transmitted back to Schenectady. At these frequencies the ionospheric induced time delay can easily approach 1 km in terms of equivalent one-way range bias. Therefore all of the VHF data was corrected (Ref. 18) using measured ionosphere sounding data in conjunction with the NASA-GSFC Ionospheric Correction Program described in Reference 19.

The Goddard antenna site during this test was ascertained from local survey maps. Once the two orbits (ATS-6 and ATS-3) were determined the ranging bursts from Rosman (or Mojave) and Schenectady to NTTF were used to solve for the site latitude and longitude. The total error in position recovery versus universal time 3 November 1974 is given in Table I. It should be noted that not

Table I

ATS-6/ATS-3 GSFC Site Determination

Universal Time (Hours)	ATS-6/NTTF Interrogation	Total Error (Meters)
0100	Rosman	168
0700	Mojave Hybrid	40
0900	Rosman	71
1100	Mojave Hybrid	969
1500	Mojave Hybrid	374
2100	Rosman	1183
2300	Mojave Hybrid	412

Note: ATS-3/NTTF interrogations all from G.E. Observatory, Schenectady, N.Y.

all of the NTTF ATS-6 interrogations are listed (refer to Fig. 2). This is due to 5 passes during which simultaneous ATS-3 and ATS-6 data was either not recorded or not satisfactory.

As a matter of interest, Table I when plotted in terms of the component North-South and East-West station location error, forms a straight line (Fig. 9). The individual components upon examination appear to have a periodic variation as seen in Figure 10. Also the ratio of North-South error to East-West error at any given time as implied by Figure 9, is essentially constant. This result is still under investigation.

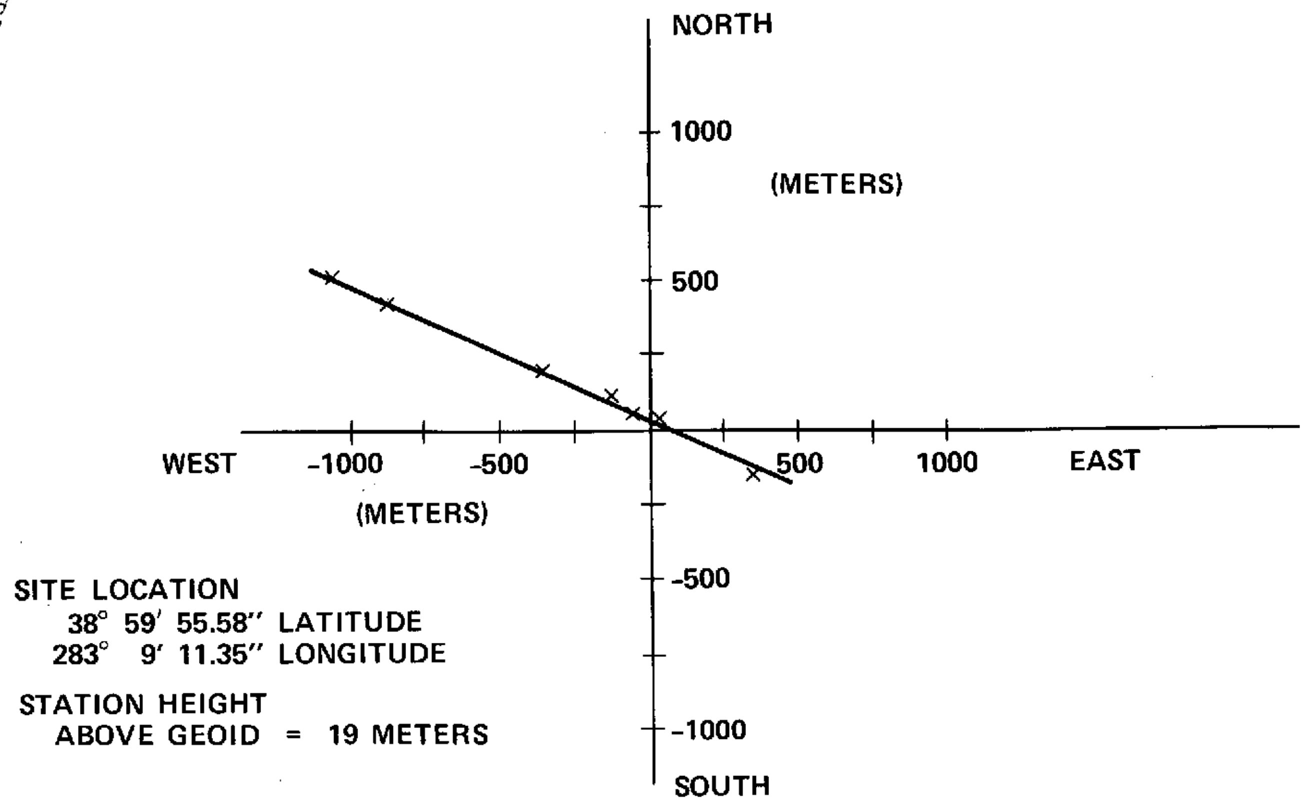

Figure 9. NTTF-GSFC Position Error

ATS-3/ATS-6 POSITION DETERMINATION OF
GSFC-NTTF TRACKING SITE

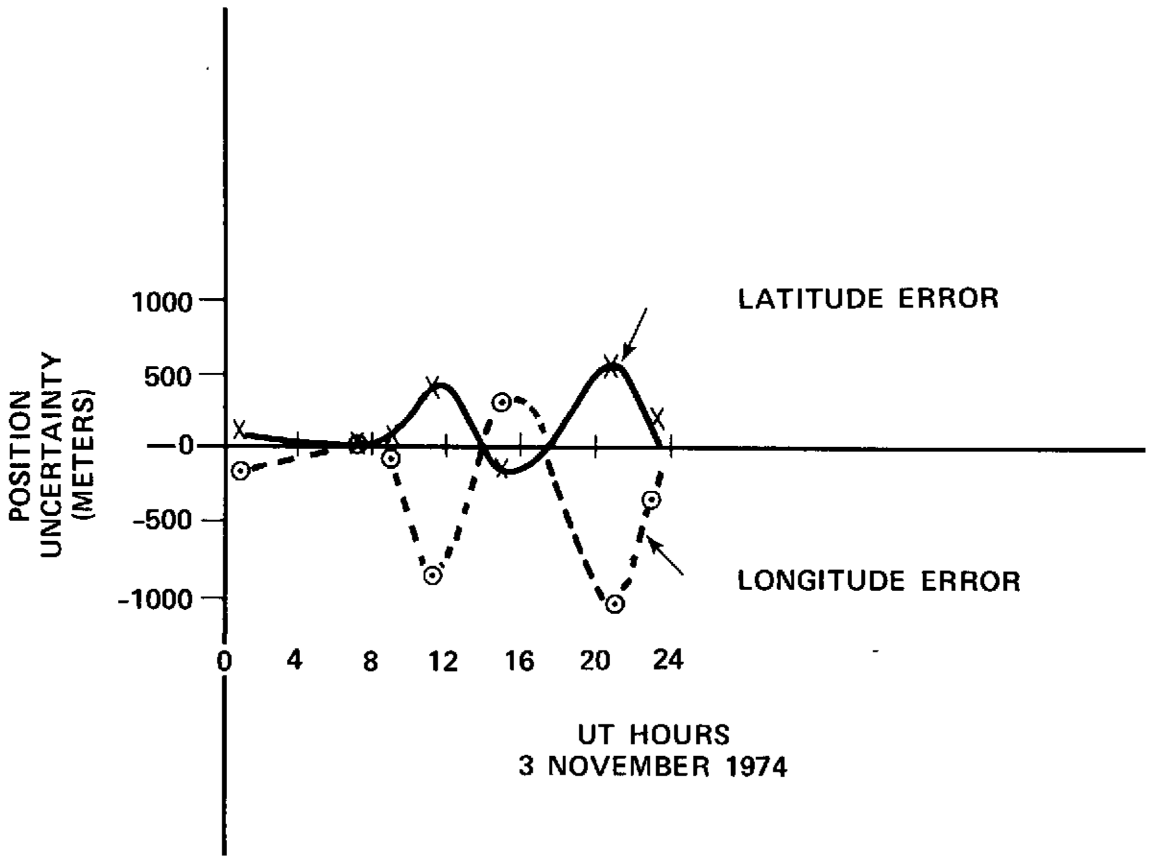

Figure 10. Time Variation of Station Determination Error

5.0 CONCLUSIONS

The ATS-6 tracking system performance is again seen to be well within specifications. The range RMS noise was observed to be 1.5 meters and the range rate RMS noise level was 0.3 mm/sec for 1 sample per 10 second data.

It has been demonstrated that a single tracking station in conjunction with several remote transponders can be used to accurately determine geostationary satellite orbits to better than 250 meters in absolute position. This represents a cost effective means for high altitude satellite orbit computation since only a single interrogation and data collection terminal is required. The transponder sites could conceivably be designed to operate on a strictly remote basis responding only when interrogated. The G.E. VHF worldwide ranging system can already operate in this manner.

Finally, two satellites so tracked can be used to obtain an Earth site position fix to better than 1 km during anytime within a 24 hour period. Further experiments will be performed to determine to what extent two satellite orbits can be propagated for Earth site position determination purposes. For example, if sufficient satellite orbit prediction accuracy is achieved it would be possible to interrogate a specific site from two satellites and determine site latitude and longitude within minutes.

The work reported herein is part of an ongoing applications study related to the ATS-6/GEOS-3 and ATS-6/NIMBUS-F satellite-to-satellite tracking experiments for which the Measurements Evaluation Branch (Code 932, NASA-GSFC) has the responsibility of evaluating.

ACKNOWLEDGMENTS

The cooperation of all participating tracking site personnel and ATS project personnel is especially acknowledged since such tracking tests are possible only as a consequence of their dedicated support.

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